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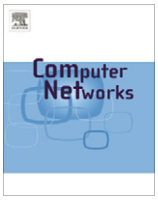

Utilizing dynamic spectrum leasing for cognitive radios in 802.11-based wireless networks ☆

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ABSTRACT

Dynamic spectrum access (DSA) is proposed to deal with the growing shortage of available leased spectrum for wireless communication. We investigate a subset of DSA referred to as dynamic spectrum leasing (DSL). At its core, DSL allows spectrum lease holders and cognitive radios to cooperate in an effort to leverage spatial diversity to improve channel utilization for both parties. In this research, cognitive radios offer their services as an intermediate relay node in an effort to improve throughput of primary users utilizing a 802.11-based channel access mechanism. In return, the cognitive radio 'piggy-backs' some of its own data while acting as a relay. In this paper, a simple coordination scheme is introduced that allows a network of Secondary Users to coordinate with a primary user network's access point. This scheme does not require any modification to the primary users' 802.11-based protocol stack as our protocol is implemented only at the access point and the Secondary Users. Analytical insights into the overhead required for this coordination and the optimization of the overhead are presented. It is shown that, given sufficient relay channel conditions, forwarding packets through a secondary relay channel can be beneficial to both parties in terms of saturation throughput.

1. Introduction

Due to the static allocation and sparse usage of licensed spectrum [1], there has been a recent surge in the research of cognitive radio technologies. Cognitive radios [2,3] are devices that have the ability to adapt their communication parameters to the current spectral environment. In general, these devices are envisioned to operate on the underutilized licensed spectrum without interfering with the licensed users. This generic description of the requirement has lead to several interpretations.

One means of avoiding interference with licensed spectrum owners, referred to as Primary Users (PUs), is called overlay communications [4,5]. Cognitive radios, referred to as Secondary Users (SUs), observe the local spectral environment, and adapt their communication parameters such that the interference they generate though communication remains below some pre-defined threshold. This interference mitigation is often achieved through frequency division multiple access (FDMA) [6–8], time division multiple access (TDMA) [9], code division multiple access (CDMA) [10,11], or some variation of traditional medium access control (MAC) techniques. In each of these examples, PUs are oblivious to the presence of SUs and see their communications as noise. However, independent of the modulation and coding schemes employed, the probability of SUs interfering with a PUs is always non-zero without a priori knowledge of PU behavior. Furthermore, this model restricts the access of SUs in case PUs fully utilize the channel. In this paper, we will argue that, even under full PU utilization of wireless resources, it is possible to accommodate SUs at no expense to PUs. On the contrary, PUs stand to improve their throughput via SUs following the methods proposed here.

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The above mentioned goals are achievable through *dynamic spectrum leasing* (DSL) [12]. Instead of scavenging unused wireless resources, cognitive radios cooperate with PUs and negotiate on-the-fly a deal whereby SUs help improve PU throughput in return for channel access. This basic concept can, in theory, alleviate the two aforementioned problems inherent with overlay cognitive radio communications. By negotiating for available spectrum, rather than blindly attempting to avoid interfering with PU transmissions, the cognitive radios can offer greater assurances of non-interference. Also, whereas excessive PU activity decreases the ability of SUs to gain channel access, we will see how DSL allows SUs to operate even under high PU traffic.

We envision DSL-based CRNs to operate in heavily congested areas where traditional interference-mitigation techniques cannot yield sufficient transmission opportunities for a SU network. The authors in [13,14] only consider cooperation between SUs in their DSL framework. While this cooperation leads to improved performance for the SU network, the effect of the SU traffic on the local PU network is not considered. Furthermore, without PU cooperation, the probability of generating unwanted interference on the PU network remains. The authors in [15,16] propose cooperation between local PUs and SUs. In this case, the SUs and PUs negotiate what level of interference the PU network can tolerate from local SUs. Through power control, the SUs then limit their generated interference to that which is acceptable and operate on what limited resources are available to them. While this technique allows PUs to negotiate what performance hit they will take, it still results in decreased performance for the PU network.

In this research, rather than negotiating with PUs to reduce the negative effect of local SUs on the PU network,our goal is to improve PU network performance by utilizing SUs as cognitive relay nodes for the PU network. In [17] cognitive relays were used between SUs to improve SU network capacity, however, this still would result in decreased performance for the PU network as the SUs simply rely on avoidance of PUs, not cooperation with them. The authors of [18,19] investigated how SU relay nodes could be used to improve certain aspects of the PU network performance. In [18] SU relay nodes were used to forward lost PU packets to improve the reliability of the PU network. In [19] SU relay nodes were used when the SNR of the direct PU link dropped below a certain threshold, thus improving the SNR of PU links when necessary.

In this paper, we introduce the concept of backwards-compatible dynamic spectrum leasing. In all of the aforementioned cognitive relay techniques, a significant requirement was placed on the PU network to support the coordination between PUs and SUs. While some form of protocol support must be available to support SU coordination, limiting the portions of the PU network affected by such requirements allows for greater applicability in scenarios where parts of the PU network do not support SU cooperation. Here, we propose an enhancement to the 802.11 infrastructure mode, which would allow a network of PUs to coordinate spectrum leasing with SUs, while remaining completely oblivious to their presence. All coordination efforts are negotiated between a centralized access point and individual SUs. This eliminates any burden on PUs by requiring no knowledge of the coordination. We envision this to applicable in large wireless 802.11-based networks where local PUs can, without their knowledge, relay packet data through cognitive relay nodes, as negotiated by a DSL-aware centralized access point.

2. System model

Our system model consists of *P* PUs communicating with a centralized access point (AP). The AP is the sink for all traffic PUs and SUs generate. All PUs utilize the standard 802.11 protocol with distributed control function (DCF). *S* SUs are also placed among PUs. All users communicate via a single communication channel that is reserved for use by the PU network. Since SUs have channel access rights, they must either transmit ‘around’ the local PU transmission (overlay) or must explicitly be given permission to communicate by the central AP. Here, we assume that all PUs operate in saturation, that is, each PU has an infinite backlog of packets ready for transmission. Therefore, opportunities for access to the channel via overlay communications are severely limited, limiting the SU network to access through dynamic spectrum leasing.

Through DSL, an SU offers to relay the PU data to the centralized access point in return for some channel utilization for its own purposes. Before this relay can take place, however, two basic conditions must be met. First, the utility of the relay channel, PU to SU (C_{ps}) and SU to AP (C_{sa}), must be at least equal to that of the direct communication channel, PU to AP (C_{pa}), for the PU to agree to the channel lease. Secondly, there must be sufficient channel capacity to allow the SU to utilize some of the relay channel for its own purposes, or the SU would not agree to assist the PU. In this paper, we measure the utility of the relay and direct communication channels in terms of throughput. When utilizing a relay channel, the original PU data packet is appended with the SU data on the second hop (SU to AP) to allow the SU some access to the data channel. To satisfy both requirements, the throughput of the relay channel, with the additional SU data, must be greater than that of the direct communication channel. To accomplish this, we opportunistically utilize the relay communication paths with favorable channel gains. We exploit the random nature of a fading communication channel to utilize the relay paths when the communication through the relay node is sufficient to meet the above requirements.

3. Protocol overview

To facilitate DSL, first, some degree of coordination is required between the PU and SU networks. To this purpose, we have designed a coordination mechanism that works with the standard 802.11 protocol to achieve backward compatibility. PUs need not be aware of the coordination, or even that they are relaying packets through SUs. The decision of which SU, if any, is used in a relay communication channel, is handled purely by the Access Point. To make this decision, the access point must first gather the channel state information (CSI) from all potential SUs.

3.1. Initialization

The transmission of channel state information to the access point from all potential SUs is triggered when a PU announces its intention to transmit a data packet via a request to send (RTS) control packet. SUs that overhear this transmission then transmit a request to cooperate (RTC) message to the AP in a slotted-CSMA manner. That is, each SU randomly selects a slot in which it will transmit its RTC message. In the slots preceding their selected transmission slot, SUs listen to the communication channel for other SU activity. If an RTC transmission is detected, the remaining RTC slots are deferred until this transmission is completed. The slotted-CSMA mechanism is illustrated in Fig. 1.

3.1.1. Initialization overhead

The information exchange between SUs and AP adds overhead to the exchange of packets between the PU and AP, whether or not a SU is selected as a relay node. Here, we analyze the coordination initialization to determine, $t_{coordinate}$, the expected time required for the RTC packet transmission given a network of S SUs utilizing the slotted-CSMA with K time slots.

The probability that a given timeslot k is idle (P_{idle}) or busy (P_{busy}) is given by

$$P_{idle} = \left(1 - \frac{1}{K}\right)^{S}, \quad P_{busy} = 1 - P_{idle}. \tag{1}$$

The probability that i time slots are idle ($0 \leqslant i \leqslant K$) is

$$P_i = \binom{K}{i} (P_{busy})^{i} (1 - P_{busy})^{K-i}. \tag{2}$$

The expected numbers of busy and idle time slots are

$$E[K_{busy}] = \sum_{i=1}^{K} iP_i = K - E[K_{idle}]. \tag{3}$$

With these expectations, we can calculate the expected overhead of the RTC message exchange. We assume the duration of an idle time slot, t_{idle}, is only one SIFS as defined in the 802.11 standard, giving other SUs sufficient time to listen and react to the current state of the communication channel. The duration of busy time slots, t_{busy}, is sufficiently long to allow the transmission of the collected CSI data and other control data. The duration of the entire RTC packet exchange can be calculated as:

$$T_{RTC} = (E[S_{idle}]t_{idle}) + (E[S_{busy}](t_{RTC} + SIFS)). \tag{4}$$

3.1.2. Initialization success

The probability that an arbitrary SU will successfully transmit its RTC packet can be computed based on S and K. We assume that if two or more SUs select the same transmission time slot, the transmissions will collide. Therefore, an RTC transmission is successful iff the transmitting SU selects a unique time slot in the current RTC message exchange. The probability, $p(S,K)$, that an arbitrary time slot contains exactly one RTC message transmission is:

$$p(S,K) = \binom{S}{1} \left(\frac{1}{K}\right) \left(1 - \frac{1}{K}\right)^{K-1}, \tag{5}$$

where $\frac{1}{K}$ is the probability that an SU selects one time slot out of K time slots. We define $m(S,K)$ as the maximum number of nodes that can be discovered in a single RTC message exchange given there are S SUs competing for K slots. $m(S,K)$ is defined as

$$m(S,K) = \begin{cases} K-1 & \text{if } S > K, \\ S & \text{if } S \leqslant K. \end{cases} \tag{6}$$

The probability of exactly one successful RTC transmission from the S SUs is given as

$$q_1(S,K) = \binom{K}{1} p(S,K) l(S-1, K-1), \tag{7}$$

where $l(S-1,K-1)$ is the probability that the none of the remaining $S-1$ timeslots contain a successful RTC transmission. Therefore, the probability $q_i(S,K)$ of discovering i nodes ($1 \leqslant i \leqslant m(S,K)$) in one RTC message exchange is

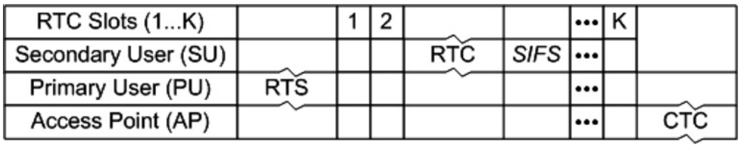
$$q_i(S,K) = \begin{cases} 1 & \text{if } S = 1, \\ 0 & \text{if } S \leqslant K, \\ & \text{and } i = K-1, \\ \binom{K}{i} \left[\prod_{j=0}^{i-1} p(S-j, K-j)\right] & \\ \times l(S-i, K-i) & \text{Otherwise}, \end{cases} \tag{8}$$

which is used to calculate the probability mass function (PMF) of the number of successful RTC transmissions in one RTC message exchange. $l(S-i,K-i)$ is the probability that none of the remaining $(K-i)$ time slots contain a successful RTC transmission:

$$l(S-i, K-i) = q_0(S-i, K-i) = 1 - \sum_{a=1}^{m(S-i,K-i)} q_a(S-i, K-i). \tag{9}$$

Finally, for a given SU, we calculate the probability of successfully transmitting an RTC packet, $p_{rtc}(S,K)$ as

$$p_{rtc}(S,K) = \frac{\sum_{i=0}^{S} i \cdot q_i(S,K)}{S}. \tag{10}$$



RTC Slots (1...K)		1	2			•••	K	
Secondary User (SU)				RTC	SIFS	•••		
Primary User (PU)	RTS					•••		
Access Point (AP)						•••		CTC

Fig. 1. 802.11 Relay initialization overview.

To verify this analysis, in Fig. 2 we compare the analytical formulation of p_{rtc} to that of a Monte-Carlo simulation setup to find the probability of success over 10,000 simulation runs.

3.2. Protocol runtime

After the AP collects the RTC message transmissions from all local SUs, it makes a decision as to which SU, if any, is selected for packet relay. This decision will be based on whether the relay communication channel through a given SU s can support a higher throughput than the direct communication path between the PU and AP. To estimate the throughput of the direct and relay communication channels, the link quality of each path must be gathered at the AP. When receiving the RTS and RTC messages the AP can collect channel state information for its link to all SUs and to the given PU. The remaining PU-SU links can be evaluated by the SUs upon receiving an RTS message. The PU-SU channel state information can then be forwarded to the AP in the RTC message. A detailed analysis of the system throughput will be given in the following section.

Immediately following the RTC message exchange, the AP announces with a clear to coordinate (CTC) message its decision on which, if any, SU will act as a relay. This decision is based on the expected throughput of the relay and direct communication channels. Based on the collected channel state information, the AP computes the estimated throughput for the direct and relay communication channels for the current transmission request, accounting for the overhead associated with relaying the SU's data and the handshaking overhead. The channel with the highest expected throughput is chosen to service the current packet exchange. If the highest expected throughput is achieved by utilizing a SU relay node, the given SU is indicated in the AP's response (CTC). If, however, no SUs are present which can offer higher throughput than the direct communication channel, the AP will respond to the PU with a CTS message, indicating to the local SUs that the direct channel will be used and initiating a standard 802.11 packet exchange with the given PU.

Here, we further discuss the timing of the protocol operation. Since PUs are not required to change their 802.11 protocol operation, any RTC-CTC exchange would lead to the expiration of the PU timers. Therefore, whenever SUs report their channel conditions and send RTC messages, PUs will be forced to transmit their RTS messages once again. When the RTS retransmission occurs, either the AP (in the case of direct communication) or the selected SU (in the case of relay communications) will respond with a clear to send (CTS) message. In the case of direct communication, the remaining handshake and packet exchange will happen according to the 802.11 standard. For relay communication, a store and forward protocol operates in three steps:

1. PU sends its data packet to the relay SU;
2. SU appends its data to the original data packet;
3. SU sends the modified data packet to the AP.

In Fig. 3 the packet sequence used to support the cooperative communication channel coordination is shown. As discussed in Section 3.1 the coordination phase is kicked off when a PU sends its RTS message to the AP, as shown in Fig. 3A. In this example, the two local SUs, SU_A and SU_B, overhear the PU's RTS message. Each SU then selects a random timeslot to transmit an RTC message to the AP, the timing of which is shown in Fig. 1. At this point, the AP has collected channel state information from each available SU as well as the PU. Based in this information, the AP decides which communication path is best to support the PU data transmission. In this example, we assume the relay communication channel through SU_A maximizes the expected throughput of the PU, and therefore, in Fig. 3C, the AP sends a CTC message to SU_A. The CTC message can also be overheard by other SUs (SU_B) indicating that they are not needed to support this packet exchange. After receiving

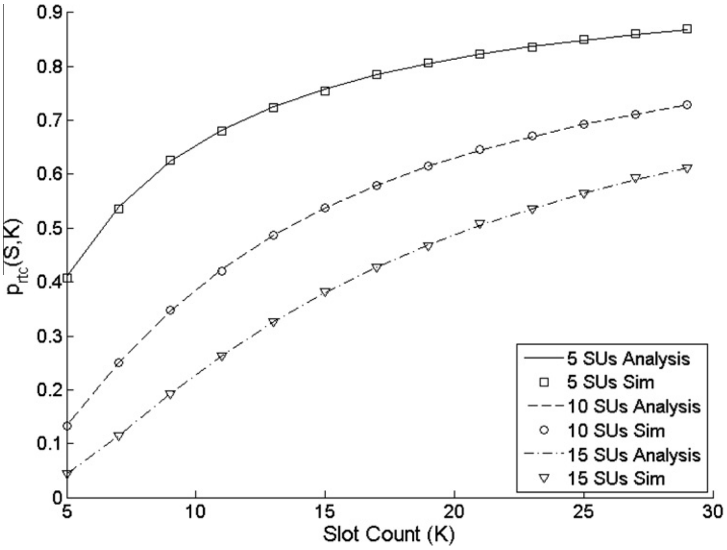


Fig. 2. Probability of RTC transmission success.

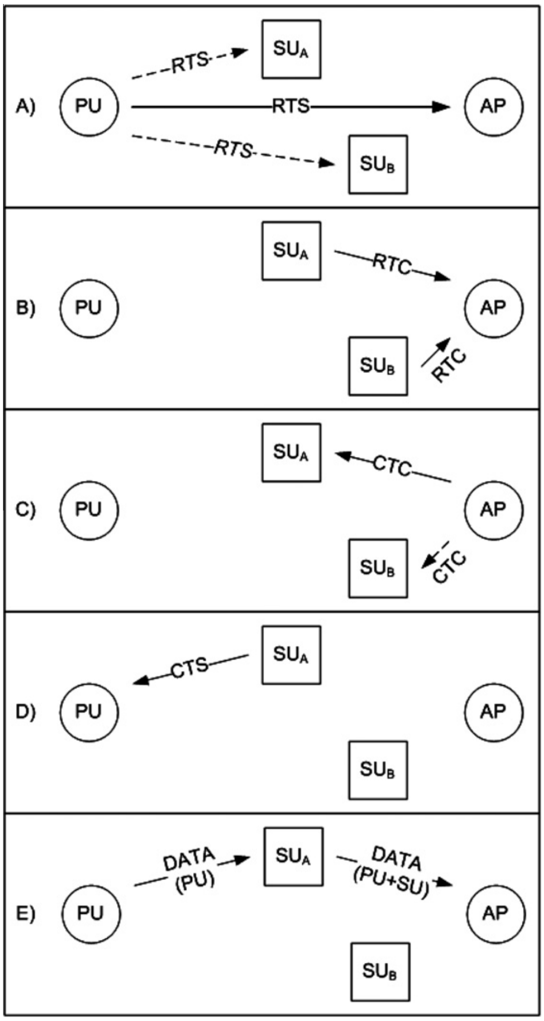


Fig. 3. 802.11 DSL packet exchange sequence.

the CTC message, SU_A will emulate the AP in sending a CTS message to the PU (Fig. 3D), which will setup the relay communication channel through SU_A. In Fig. 3E we see the PU data is sent to SU_A which appends its information to the packet and forwards the full data packet to the AP.

4. Analysis

In this section, we analyze the throughput gain via DSL. To improve the overall PU system throughput requires sufficient signal quality on the relay communication channel such that the 802.11 data rate can be increased. In general, higher data rates are achieved by either utilizing a more complex modulation scheme, or by increasing the forward error correction (FEC) coding rate. In each case, the data rate increase is dependent on the signal to noise ratio (SNR) of the communication channel. In this paper, we consider the 802.11a data rates for the following modulation schemes:

(1) binary phase shift key (BPSK);
(2) quadrature phase shift key (QPSK);
(3) quadrature amplitude modulation (QAM-16);
(4) QAM-64 (6 bits/symbol).

For any given communication channel, the SNR of the channel determines which of these modulation schemes can be utilized. In this research, for each SNR calculated, we utilize the best modulation scheme while keeping the bit error rate (BER) of the channel below 10^{-5}. For this research we use well-known BER curves [20] for each modulation scheme.

Each relay communication channel, $C_{re}(r_i,r_j)$, consists of two distinct point-to-point communication channels. Furthermore, the amount of data transmitted on the second hop of the relay channel is increased due to the additional SU data. The cooperative channel throughput for the xth PU transmission attempt is calculated as

$$Th_c^{(x)} = \max\left\{Th_d(r_1), Th_r(r_2,r_3)^{(s)},\ s = 1,\cdot,S\right\}, \tag{11}$$

where r_1, r_2, and r_3 are the channel data rates as defined in Fig. 4 for the direct and relay communication channels, S is the number of SUs, $Th_d(r_1)$ is the throughput of the direct channel at rate r_1, and $Th_r(r_2,r_3)^{(s)}$ the throughput of the relay channel through SU s at rates r_2 and r_3. The remainder of this section describes how, for the given channel data rates, we estimate the throughput of the direct and relay communication channels (Th_d and Th_r).

The saturation throughput of a standard 802.11 network has been thoroughly studied in [21]. In this paper, we make several modifications to this study to account for the overhead associated with dynamic spectrum leasing. To calculate the expected throughput for a given data rate, we utilize a Markov Chain analysis of the distributed coordination function (DCF) backoff mechanism as shown in Fig. 5. Each row in the 2-dimensional Markov Chain represents a backoff stage for an arbitrary PU. When the backoff counter for a given PU reaches zero, represented by state 1 in any of the m backoff stages, the PU will attempt transmission by transmitting an RTS packet. In this paper, we assume that PUs utilize the RTS/CTS handshaking for all communications. Therefore, the probability that an arbitrary PU attempts transmission is

$$\tau = \sum_{i=0}^{m} p(i,1), \tag{12}$$

where $p(i,j)$ is the steady state probability that the backoff counter is equal to j in backoff stage i. Following the analysis in [21], we calculate the steady state probability of τ as

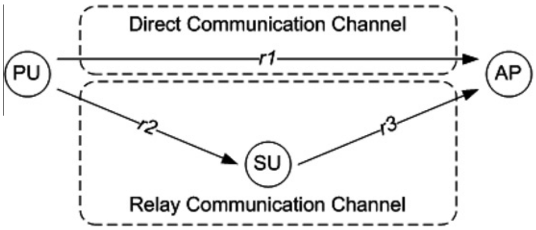


Fig. 4. Channel rate definitions.

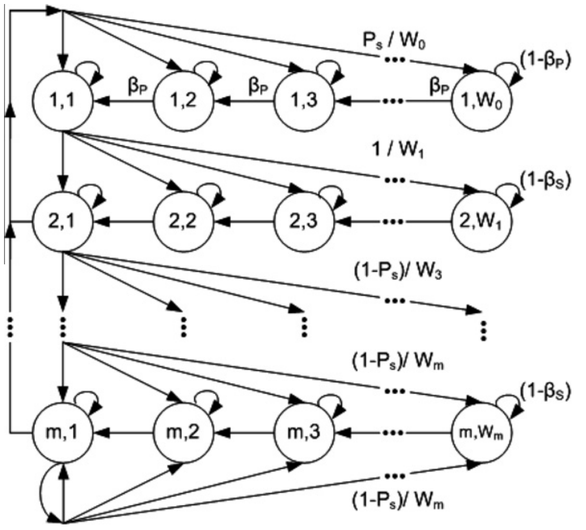


Fig. 5. Modified 802.11 DCF backoff model.

$$\tau = \frac{1 - P^{L+1}}{\left(\sum_{j=0}^{L}\left[1 + \frac{1}{P_{trans}}\sum_{k=1}^{W_j-1}\right]P^j\right)(1 - P)}, \tag{13}$$

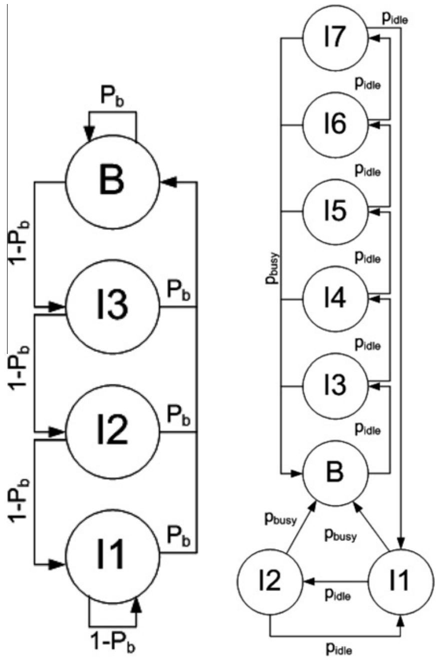
where $L + 1$ is the maximum number of retransmissions before dropping the packet, P is the probability that one of the N PUs attempt a transmission, and W_j is window size in backoff stage j. The probability P is calculated as

$$P = 1 - (1 - \tau)^N, \tag{14}$$

where N is the number of contending PUs.

In our research, the probability τ differs from that found in [21] in that the probability of a backoff counter transition, P_{trans}, is not 1. According to the 802.11 standards, a user's backoff counter will freeze if interference is detected on the communication channel during DCF backoff. The user's backoff will then only continue after the medium has remained idle for DIFS time (50 μs). During periods when no PUs are transmitting data, PUs can decrement their backoff counters unimpeded. However, during successful transmissions, there are two sources of interference that can freeze a PU's backoff counter, local primary and secondary users. During the idle periods of a successful transmission, the transition probability, $P_{PUtrans}$, is determined by the steady state probability of being in state $I1$ of the Markov Chain model in Fig. 6(a). When a PU in DCF backoff detects activity in a given backoff stage, it will immediately freeze its backoff counter, as represented by state 'B'. As long as the medium remains busy, this PU will not decrement its backoff counter. However, if the PU detect three idle timeslots, that is, if the medium remains idle for more than the required 50 μs, as defined by the 802.11 standards, it will reach state '$I1$' and transition to the next backoff timeslot.

In the same manner, while SUs are exchanging their RTC control packets, there is a probability, $P_{SUtrans}$, that there are sufficient idle RTC time slots to allow local PUs to reduce their backoff counters. In Section 3.1.1 we define the duration of an idle RTC timeslot as one SIFS (10 μs). Therefore, for a PU to transition to a new backoff slot, there must be two sequential idle RTC timeslots as represented by states $I1$ and $I2$ in Fig. 6(b). However, given a busy RTC timeslot, the PU(s) will freeze their backoff timers and enter state $I7$ in Fig. 6(b), and only continue to backoff after sufficient idle timeslots have occurred. Therefore, during the initialization phase, the probability for a given PU to transition its DCF backoff counter is represented by the probability of being in state $I1$ of Fig. 6(b). In general, the probability, P_{trans}, of a PU decrementing its backoff counter is



(a) Primary User (b) Secondary User

Fig. 6. Backoff model for transition probabilities.

$$P_{trans} = P_s\left(\frac{P_{SUtrans} \cdot t_{coord} + P_{PUtrans} \cdot t_{idle(2)}}{t_{total}}\right) + (1 - P_b), \tag{15}$$

where P_s is the probability of successfully transmitting a message, and P_b is the probability that the medium is busy due to a PU transmission.

Given the probability that an arbitrary PU is transmitting a packet, we can calculate P_b that the medium is busy due to PU activity as

$$P_b = 1 - (1 - \tau)^N \tag{16}$$

and the conditional success probability of a PU transmission as

$$P_s = N \times \tau(1 - \tau)^{N-1}, \tag{17}$$

where N is the number of local PUs.

Using these probabilities, we calculate the expected throughput of an arbitrary PU as

$$Th = \frac{P_s E[D]}{P_s T_s + (1 - P_s) T_c}, \tag{18}$$

where P_s is the probability of successfully transmitting a packet, T_s is the time required to transmit a successful packet, T_c is the time required to detect a packet collision, and $E[D]$ is the expected size of the PU data in a packet exchange.

In Eq. 18, we see that the PU throughput is dependent on the total duration of the packet exchange. In the case of a successful packet exchange there are two possible values for T_s as shown in Fig. 7. The value of T_s to use for the calculation of the expected PU throughput depends on whether of a SU is selected to act as a relay communication node. In both cases, there are common elements used for the calculation of T_s. The values of t_{rts}, t_{cts}, and t_{ack} can be determined by calculating the standard 802.11 control packets being sent at the base data rate of 1 Mbps. The duration of the coordination phase, t_{coord}, is dependent on the number of SUs and the number of RTC timeslots, as defined in Section 3.1. After coordination and prior to the PU's RTS retransmission, the medium will be idle for $t_{idle(1)}$ as the PU's backoff counter decrements to zero:

$$t_{idle(1)} = (E[slot] - E[transition]) \times t_{slot}, \tag{19}$$

where $E[slot]$ is the expected number of backoff transmissions required before the PU will retransmit an RTS message, $E[transition]$ is the expected number of backoff slot transitions during the SU coordination phase, and t_{slot} is the duration of one backoff slot according to the 802.11 DCF standards. After the current transmission ends, in both cases, the medium will be idle for $t_{idle(2)}$ before another packet transmission will be attempted and is calculated as $t_{idle(2)} = \frac{1}{P} - 1$.

The calculation of T_s with a SU relay node differs from that of the direct PU-AP T_s calculation mainly due to the additional hop required between the SU and the AP. This extra hop adds some control overhead, as seen by the additional ACK message in Fig. 7, as well as an additional data packet transmission. When considering the direct communication channel, a single data transmission is required, which lasts $t_{data(d)}$ s and is dependent on the data rate of the direct communication channel, r_1. The relay communication channel requires a two-hop data transmission. The duration of the first hop (PU to SU) is $t_{data(1)}$ and is dependent on the size of the PU data packet and the data rate of the first relay channel, r_2. The second hop (SU to AP) includes the PU data as well as the additional SU data overhead and is dependent on the data rate of the second relay channel, r_2.

To calculate the expected throughput of the direct and relay communication channels, we calculate the durations of successful packet exchanges for the direct $\left(T_s^d\right)$ and relay (T_s^r) communication channels as

$$T_s^d = 2t_{rts} + t_{coord} + t_{idle(1)} + t_{cts} + t_{data(d)} + t_{ack} + t_{idle(2)} \quad \text{and} \tag{20}$$

$$T_s^r = 2t_{rts} + t_{coord} + t_{idle(1)} + t_{cts} + t_{data(1)} + t_{data(2)} + 2t_{ack} + t_{idle(2)}. \tag{21}$$

Therefore, we calculate the expected throughput of the direct communication channel as

$$Th_d(r_1) = \frac{P_s E[D]}{P_s T_s^d + (1 - P_s) T_c} \tag{22}$$

and the expected throughput of the relay communication channel as

$$Th_r(r_2, r_3) = \frac{P_s E[D]}{P_s T_s^r + (1 - P_s) T_c}. \tag{23}$$

In the following section, we show that the expected PU throughput, as calculated in Eqs. 22 and 23, can be increased given sufficient SU relay channel conditions. Furthermore, we show that the expected throughput of PUs can remain above that of the baseline 802.11 protocol with adaptive rate selection even with additional data originating from SUs. As such, both PUs as well as SUs benefit from DSL.

5. Results

5.1. Analytical results

Our analysis shows what throughput should be expected for a given communication link based on the data rate at which the packets are sent. For our analysis, we assume that the direct point-to-point PU to AP link is a fairly weak signal and therefore, the data is sent at the base data rate of 1 Mbps, as defined in Section 4. If a higher data rate could be achieved through the direct data communication channel, the data rates presented for the relay communication channel would not be sufficient to support relay communications. However, if more complex modulation schemes with higher supported data rates were considered, this concept could easily be extended for higher data rate systems.

At the base data rate of 1 Mbps, we define two expected throughput values for the direct link, the baseline

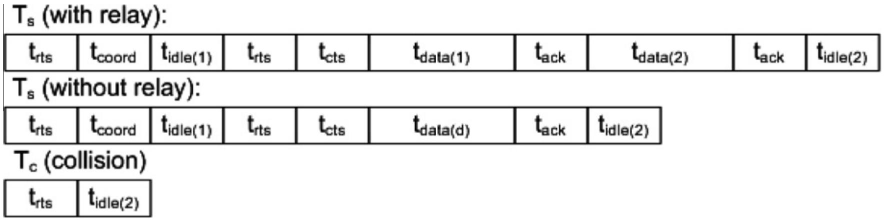


Fig. 7. Modified 802.11 time slot overview.

throughput ($TH_{baseline}$) and the direct cooperative throughput (TH_{direct}). To calculate $TH_{baseline}$, we do not consider any coordination overhead from the SU network. Therefore, this is the expected throughput of a baseline 802.11 PU network. For any SU network to coexist on this channel, the expected throughput of the cooperative channel ($TH_{cooperative}$) must exceed $TH_{baseline}$ or the SU network would not satisfy the requirement to not degrade the PU network performance. TH_{direct} is the expected throughput of the direct PU-AP link with SU overhead included. If cooperation is considered, there is a possibility that none of the potential SU relay nodes have sufficient channel conditions to act as a relay node. Therefore, the packet will be sent at the same data rate as the baseline 802.11 model, however, due to the added overhead from SU coordination, the throughput of the direct link will be lower. Based on our analysis of the network, the base PU throughput ($TH_{baseline}$) is 0.81 Mbps. In the following section, we describe the extensive Monte-Carlo simulations which were used to determine the expected performance of the cooperative relay channel. During these simulations, the preprocessed throughput calculations, a subset of which is presented in Table 1, were used.

Table 1 shows the expected throughput of the direct and relay channels, normalized with respect to the baseline throughput of 0.81 Mbps. The system parameters S and K are the number of SUs in the system and the number of RTC timeslots available, respectively. These parameters directly affect the probability that an SU will successfully transmit its RTC message (p_{rtc}). Also, we can see that, by increasing S and K, the coordination overhead is increased, resulting in reduced PU throughput for both the direct and relay communication channels. The data rates r_2 and r_3 refer to the achievable data rates for the two hops of the relay communication channel, as defined in Fig. 4.

5.2. Simulation results

In this section, we present numerical results obtained through Monte-Carlo simulations of the DSL system. To this end, we consider a system consisting of 10 PUs and S randomly placed SUs that may help increase the PU throughput within the DSL framework. In return, the SUs are permitted to piggy-back data equivalent to a given fraction of the PU payload. In all simulations, PUs send 1500 bytes of user data through either the direct or relay communication channels per packet. The amount of data sent by SUs while utilizing the relay communication channel varies as indicated on the result graphs. We use the optimization technique of Section 5.3 to select the minimum amount of overhead with a success probability of 70% for RTC transmissions unless otherwise noted.

In our throughput analysis, we use the base data rate of 1 Mbps for all physical layer header information. Control and data packet information at higher layers is sent at the maximum sustainable data rate as determined by the instantaneous channel conditions as determined by the free-space attenuation and the Rayleigh fading ($\sigma = 3$) as described in Section 4. We assume a base symbol rate of 1 mega-symbol per second as in [20], which, due to the symbol data rates, results in data rates 1 Mbps (BPSK), 2 Mbps (QPSK), 4 Mbps (16-QAM), and 6 Mbps (64-QAM). For each PU transmission attempt, we compute the throughput of the baseline and cooperative communication channels. The cooperative channel throughput is either determined by the direct PU-AP throughput (with overhead included) or the relay communication channel (from Table 1), whichever is expected to be higher. The presented results reflect averages of 10,000 transmission attempts.

In Fig. 8, we show the expected throughput of DSL and baseline 802.11 channels with varying amounts of SU data. The percentage for these results refer to the size of the SU data package as compared to the 1500 byte PU data packet. These results show the throughput from the perspective of the PU. As we can see, the throughput of the cooperative channel initially increases due to the increased probability of finding a SU with sufficient channel conditions to support relay communication. However, the improved throughput through this channel is quickly diminished as the initialization overhead resulting from a higher number of SUs increases the communication overhead, and consequently reduces the achievable throughput, even below the performance of baseline 802.11 implementation that ignores channel diversity. We observe that increasing the number of SUs is not necessarily advantageous from PUs' perspective due to increased overhead. These results also illustrate a limit to the amount of SU overhead that can be added to the system. In further research, we can consider an extension to this approach which dynamically adjusts the amount of data transmitted by the SUs as a tuning parameter to maximize the throughput of the SU network while maintaining a PU throughput greater than that of the baseline 802.11 model.

In Fig. 9, we see the expected throughput of the SU network under DSL. When a PU utilizes the relay communication channel, a portion of the communication channel is utilized for SU communication, as defined in Section 3.2. If, however, a direct communication path is utilized, the expected throughput for the SU network is zero, as no SU data is transmitted through the direct communication channel. In Fig. 9 we see that, with very few SUs, the SU network has less opportunities to act as relay nodes, and therefore, the aggregate throughput of the SU network is low. As the number of SUs increase, the opportunities for SU transmission increase to a certain point. However, as was seen in Fig. 8, at a certain point, the overhead of the SUs becomes detrimental to the PU throughput. This negative effect on the PU throughput, combined with the increased contention between the SUs for access to the RTC timeslots, reduces the expected throughput of the SU network. These results suggest that limiting the number of SUs participating in the RTC-CTC phase is very important to attain highest level of benefits from DSL.

5.3. Overhead reduction

To improve the performance of the PU network, it is necessary to limit the amount of overhead produced by the SU network. Here, we take two approaches to limiting the SU network overhead: reducing the number of SUs which generate overhead and properly selecting the number of RTC

Table 1
Achievable normalized rates through direct and relay links for direct link with BPSK modulation.

S, K	p_{rtc}	Direct (BPSK)			r_3			
					BPSK	QPSK	QAM-16	QAM-64
2, 8	0.875	0.94	r_2	BPSK	0.46	0.58	0.65	0.69
				QPSK	0.62	0.84	1.01	1.09
				QAM-16	0.75	1.08	1.39	1.54
				QAM-64	0.80	1.20	1.59	1.79
4, 8	0.670	0.91	r_2	BPSK	0.46	0.57	0.64	0.67
				QPSK	0.61	0.82	0.99	1.06
				QAM-16	0.73	1.06	1.35	1.49
				QAM-64	0.79	1.17	1.54	1.73
8, 8	0.393	0.88	r_2	BPSK	0.45	0.55	0.63	0.65
				QPSK	0.60	0.80	0.96	1.02
				QAM-16	0.72	1.02	1.30	1.43
				QAM-64	0.77	1.13	1.48	1.65
16, 8	0.135	0.86	r_2	BPSK	0.44	0.54	0.61	0.64
				QPSK	0.59	0.78	0.93	0.99
				QAM-16	0.70	1.00	1.26	1.38
				QAM-64	0.75	1.10	1.42	1.58
2, 16	0.938	0.93	r_2	BPSK	0.46	0.57	0.65	0.68
				QPSK	0.62	0.83	1.01	1.08
				QAM-16	0.74	1.07	1.38	1.53
				QAM-64	0.79	1.19	1.58	1.77
4, 16	0.824	0.90	r_2	BPSK	0.46	0.56	0.64	0.67
				QPSK	0.61	0.81	0.98	1.05
				QAM-16	0.73	1.04	1.33	1.47
				QAM-64	0.78	1.15	1.52	1.70
8, 16	0.637	0.86	r_2	BPSK	0.44	0.54	0.61	0.64
				QPSK	0.59	0.78	0.93	1.00
				QAM-16	0.71	1.00	1.26	1.38
				QAM-64	0.76	1.10	1.43	1.59
16, 16	0.380	0.81	r_2	BPSK	0.43	0.52	0.59	0.61
				QPSK	0.57	0.74	0.88	0.94
				QAM-16	0.68	0.95	1.18	1.28
				QAM-64	0.73	1.04	1.33	1.46

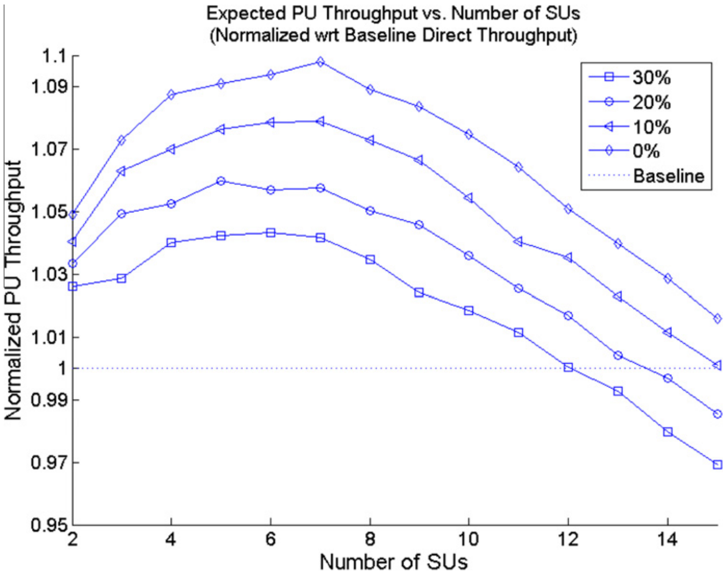


Fig. 8. Expected PU saturation throughput.

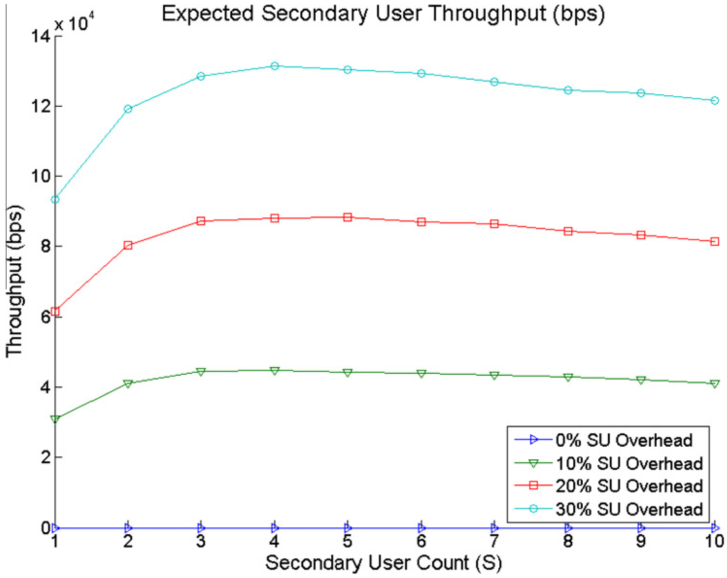


Fig. 9. Expected SU throughput.

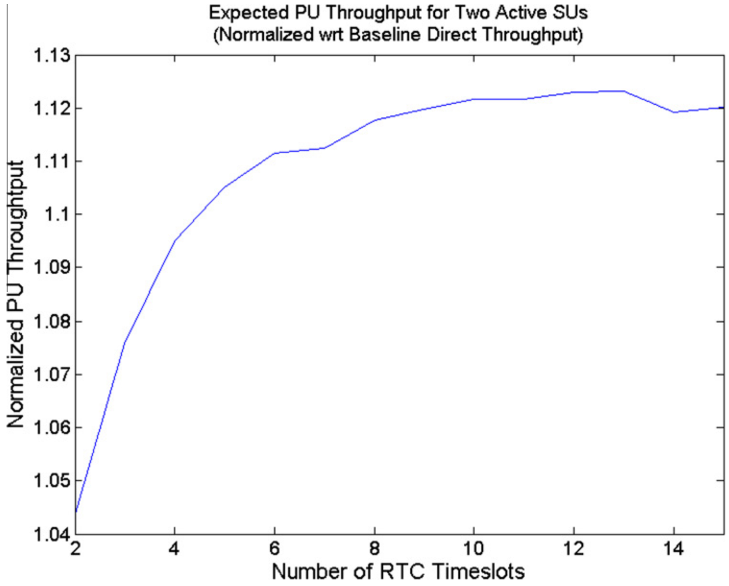


Fig. 10. Normalized PU throughput for two active SUs.

timeslots. The first approach aims to reduce the coordination overhead between the SUs and the AP. The second approach is a tradeoff between reducing coordination overhead and increasing the probability of success for the active SUs RTC transmissions.

The first approach, reducing the number of SUs generating overhead, can be handled at runtime by disallowing SUs with unfavorable channel conditions from transmitting RTC packets to the AP. As we can see in Table 1, there are many combinations of channel conditions in which the SU cannot improve upon the baseline PU throughput, specifically, where the normalized relay throughput is less than one. In these cases, by transmitting an RTC message to the AP, the SU is increasing the coordination delay and therefore decreasing the expected PU throughput, without the possibility of any gain in terms of PU throughput. Therefore, SUs with such channel conditions, should remain silent until their channel conditions improve.

Table 2
Number of RTC timeslots used for various simulations.

Number of SUs	Number of RTC timeslots
2 thru 7	12
8 thru 14	13
15 thru 20	14

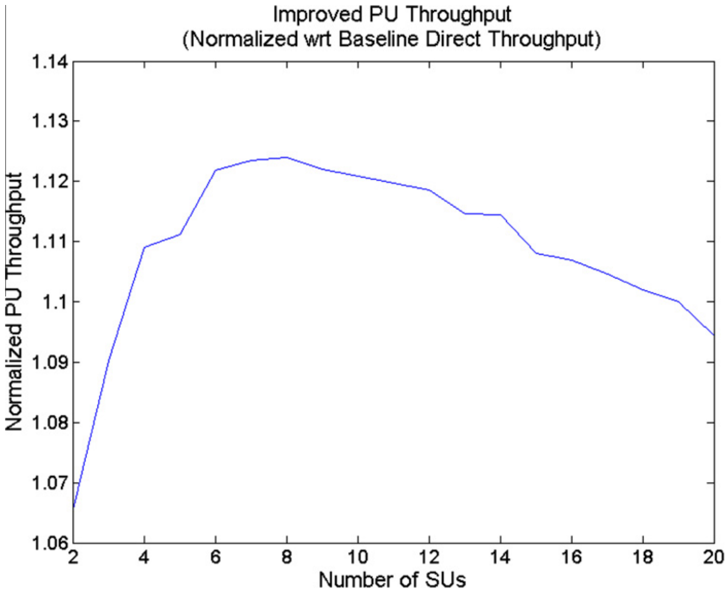


Fig. 11. Expected PU throughput with reduced SU overhead.

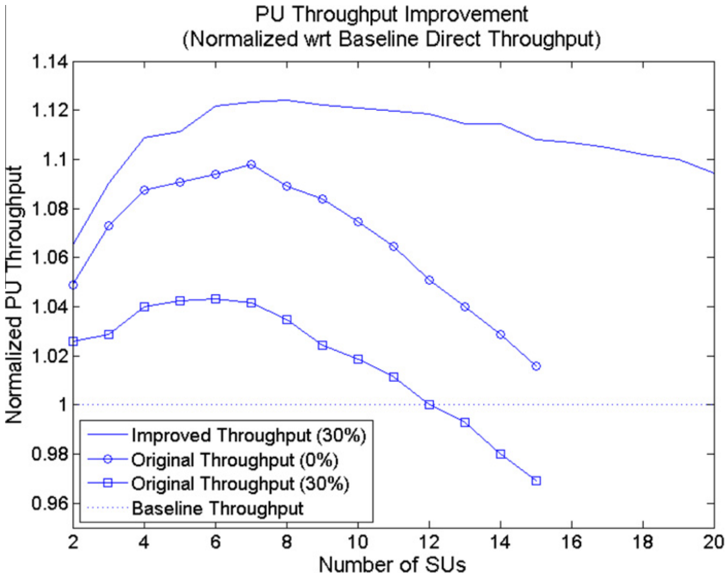


Fig. 12. Comparison of original and improved expected PU throughput.

The second approach, reducing the number of RTC timeslots, is based on our simulation observations. For a given number of active SUs, that is, SUs which have sufficient channel conditions to transmit RTC packets, we have run multiple simulations to determine how many RTC timeslots are necessary to achieve maximal throughput. In Fig. 10, we see the expected PU throughput when two SUs are active. As you can see, with approximately 12 RTC timeslots, the throughput of the PU levels and then begins to decrease. It is important to note that this result only considers 2 'active' SUs, there may be more SUs in the simulation with insufficient channel conditions to participate in the coordination phase. In our simulation runs, approximately 40% of the SUs are active, therefore, for simulations with up to seven SUs, we utilize 12 RTC timeslots. In Table 2, we show the number of RTC timeslots utilized for a given number of SUs in the simulation area. When considering different network topologies or other modulation techniques, the proper number of RTC timeslots can be estimated and programmed into the AP.

In Fig. 11, we see the expected PU throughput with the coordination overhead reduced. As you can see, the throughput of the PU is improved in all simulation results. These simulations were performed with 30% overhead from the SU networks. In Fig. 12, we see the direct comparison between the original results at 30% overhead, and the improved results.

6. Conclusions and future work

In this work, we presented a 802.11-backward-compatible protocol that facilitates dynamic spectrum leasing. Under the DSL framework, PUs are still oblivious to the presence of SUs, but the access points are not. Moreover, PUs do not change their implementation of the 802.11 protocol. The main idea behind DSL is to capitalize on diversity in different channels in the network. SUs provide possible relay points to PU data so as to improve the throughput of PUs. In return, SUs are granted permission to piggy-back their own data to the relayed PU data. The AP in the system collects the channel conditions from SUs via a specialized handshaking message sequence and selects the direct or relay path with highest expected throughput. Although ideally DSL is guaranteed not to perform worse than the baseline system without SUs, any practical implementation is bound to induce overhead, which is further exacerbated by backward compatibility requirements of the protocols. We provided analytical tools to scrutinize the performance of the proposed protocols and showed through simulations that our proposed protocol improves the PU throughput above the 802.11 baseline and provides SUs to transmit their own data, without requiring PUs to change their protocol implementations. In our future work, we aim to validate our DSL protocol with a proof-of-concept implementation and test alternative methods to reduce the contention among SUs by eliminating and discouraging SU with poor channel conditions. Furthermore, we will carefully analyze the security aspects of the proposed approach and try to incorporate data privacy and defenses against malicious SU operations.

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